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Discussion and Conclusion

The reflection of the second-order ripple at the input of the single-phase inverter is an inherent and inevitable phenomenon. The ripple back-propagates from the DC input of the inverter to the source and injects into the source directly or through the intermediate converter or circuit between the DC source and inverter. This ripple results into several adverse effects on the system related to efficiency, reliability, stability, size, cost and life of the system. In this Thesis, the solutions for the minimization of the second-order ripple at the input of the boost-derived two-stage DC-DC-AC converter and quasi-switched boost inverter have been addressed. For the mitigation of the SHC-ripple, new nonlinear controllers have been proposed. The proposed controllers mitigate the ripple-problem along with the desired dynamic performance of the system at the line-load transients. The stability and the performance of different non-linear controllers have been investigated. The proposed theoretical developments have been validated through the simulation and experimentation. Moreover, a study on the second-order ripple in the DC microgrid having multiple loads has been carried out. A new method of phase-adjustment based ripple cancellation at the DC bus for a system having two inverter loads connected at the DC bus has been proposed. In this Chapter, the findings of the work and associated challenges and recommendations to carry forward the future research will be discussed.

The Thesis begins with introduction to second-order ripple problem in the single-phase inverters followed by a comprehensive review of the literature, the motivation and objective, proposed work and future scope and challenges. Several control techniques for the $2\omega-$ripple problem in the single-phase inverter have been reviewed. Though the available control techniques mitigate the $2\omega-$ripple problem in the single-phase inverters, however, these techniques involve various challenges. The use of E-cap is most simple and conventional technique. However, other than the cost, size and weight of the E-cap, the reliability of the E-cap is the major challenge. Even though the film-capacitor minimizes the reliability problem, it adds the cost, weight and size to the system in the same proportion. Nevertheless, a small size film capacitor is used in the active filters. The application of AC-side or mixed-type active power-decoupling techniques interfere the main H-bridge circuit, this poses various challenges related to modulation index, utilization of the power-electronics devices, control design and stress on the system components. The dual-loop control scheme and output-impedance shaping scheme are two popular control-oriented compensation techniques which are used in the two-stage DC-DC-AC converters. The main challenge in these techniques is to maintain good dynamic performance along with SHC ripple reduction at the input. The addition of resonant filter in the current or voltage loop has shown improved dynamic performance. However, this limits the bandwidth of the system and also the design of resonant filter is another challenge; a poor design of resonant filter may induce instability. In this Thesis, the important challenges i.e. the mitigation of SHC ripple problem along with the desired system dynamics and ensuring the robustness against disturbances/uncertainty and the stability at the large line-load transients have been resolved. The conclusion of the work is as follows,

An adaptive sliding mode controller has been proposed to mitigate the SHC ripple at the input of the two-stage boost-derived DC-DC-AC converter. The basic concept of the ripple reduction and improvement in system dynamics is based on the shaping of the output impedance. The proposed controller modifies the output impedance of the front-end DC-DC converter such that the propagation of SHC ripple is resisted in the direction of the DC source and hence protect the source from the adverse effects of the SHC ripple. The proposed controller minimizes the SHC ripple at the input and keeps its peak to peak value within 1% with respect to average input current value. The adaptive nature of the proposed controller improves the dynamic performance. At the load transients from no-load to full-load and vice-versa, the undershoot/overshoot in the DC link voltage with respect to the reference voltage are -8% / $+3\%$. The negligible undershoot and overshoot in the DC-link voltage were observed at the line-transients.

The quasi-switched boost inverter is one of the converters from the impedance source inverter family. This converter have capability to boost the value of input voltage without adding extra front-end converter. Moreover, unlike voltage source inverter, the q-SBI works safely at the undesired short-circuiting of the switches belonging to the same leg(s) of inverter. The quasi-switched boost inverter has been considered in the second work. A modified version of the nonlinear controller as proposed in the first work has been implemented with quasi-switched boost inverter. The concept of the SHC ripple mitigation is based on the output impedance shaping. The SHC ripple in the input current of quasi-switched boost inverter is less than 5%. The undershoot and overshoot are less then 18.5% of the reference DC-link voltage at the load transients, and the overshoot and undershoot are negligible at the line transients. The size of the capacitor and inductor required are smaller in comparison to the existing work in the literature.

The classical control methodologies have been widely used for the mitigation of SHC ripple problem. However, the classical control ensures stability close to operating point. The nonlinear controls are preferred for the system having the frequent large line-load transients and uncertainty in the system parameters. To achieve this, an integral sliding mode (ISM) based control have been proposed in the third work. The integral sliding mode control ensures the robustness against the disturbances/uncertainty from the beginning of the system response and allows the classical control methodologies to combine with the sliding mode control. A boost-derived DC-DC-AC converter has been considered to implement the proposed ISM based control technique. A new adaptive PI-controller associated in the dual-loop control has been proposed as the nominal control to design the integral sliding mode control. The proposed ISM based controller mitigates SHC ripple problem, improves the system dynamics and adds invariance property to the system. The performance of ISM based controller has been validated through the experimentation. The nominal controller reduces the SHC ripple in the input current and keep its value less than 7.7%. However, a 50% (approx.) reduction in the size of the system parameters (inductance, L and capacitance, C) increases the ripple to 15%. With the proposed ISM based controller, the ripple reduces to a negligible value. Furthermore, the proposed controller eliminates the effect of the disturbances entering through the control input.

In the previous contributions, the stand-alone single converter has been considered. In the fourth contribution, firstly, a study on the second-order ripple has been carried-out for a typical DC microgrid having multiple inverter loads. Secondly, a phase-adjustment control technique has been proposed for the ripple mitigation at the DC bus that supplies two inverter loads. The basic concept is to control the required phase difference between the output voltages of the inverters such that $2\omega-$ripple reflected at the DC-bus by the first inverter is canceled by $2\omega-$ripple reflected by the second inverter due to phase opposition of the ripples at the DC bus. For the same loading of the inverters, the ripples cancel each other at the DC bus. For different loading condition of the inverters, the equivalent ripple is available after cancellation due to the different current loading of inverters. Therefore, the modulation indices are varied for the further minimization of the equivalent ripple at the DC bus. The performance of the proposed controller has been validated through simulation.

Recommendations for Future Work and Some Open Problems

Based on the work carried-out in this Thesis and the work presented in existing literature, the associated challenges in the mitigation of $2\omega-$ripple are discussed here. The reliability on the healthy working of electrolytic capacitor in the presence of the second-order ripple is questionable. The active power-decoupling techniques are to be explored which do not affect modulation index of inverter, ensure better utilization of the devices and reduce the voltage/current stress on the devices (switches, inductors, capacitors) for the operation of inverter at the different power factors. The work is required to design the new single-phase converter topologies that are cost-effective, efficient and capable of $2\omega-$ripple mitigation for today's smart power applications. The control techniques can mitigate the ripple problem in single-phase inverters. The linear control methodologies have been widely used to mitigate ripple-problem in the single-phase inverters, however, these methodologies ensure stability close to the operating point only. The work is required to guarantee stability at large line/load transients. Moreover, the disturbances/uncertainty such as parametric variations, modeling error etc involve in the applications of actual power converters or inverters. The linear controls are sensitive to disturbances. The linear controls compromise among the robustness, stability and dynamic performance. Therefore, there is need of robust control techniques which mitigate ripple-problem along with uncertainty/disturbances.

The new nonlinear control techniques have been proposed in present work. The proposed work mitigates the SHC ripple along with the desired dynamic performance. The present work, however, to be explored further in the different aspects. For this, the recommendations for future research are as follows

- The present work focuses on the off-grid system, however, the present work can be extended to investigate the performance of the proposed control techniques in the grid-connected systems.

- The present work have considered only single-phase inverters. The three-phase inverters have the second-order ripple problem at the unbalanced load condition and the three-phase inverter are generally loaded by unbalanced loads. Therefore, the present work can be extended in the three-phase inverters having the unbalance load conditions.

- The present work have proposed non-linear controllers to mitigate the SHC ripple at the input of the two-stage DC-DC-AC converter and quasi-switched boost inverter. The ripple is reduced at the input of the considered converters, however, the ripple is confined at the DC-link of the inverter. The optimum size DC-link capacitor has been used with the proposed controllers. The proposed controllers achieve desired dynamic performance of the system at the load-line transients, however, a part of the $2\omega-$ripple still exists at the DC-link due to small capacitance at the DC-link. Therefore, there is further need to eliminate the $2\omega-$ripple at the DC-link of the inverter without adding extra electrolytic capacitance. For this, the active power-decoupling techniques are to be explored.

- The present work can be extended to investigate the performance of the proposed control techniques in the microgrid.

- The power factor correction converters also suffer the second-order ripple problem, therefore the new nonlinear control techniques can be explored to implement in such converters.